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Analysis of Cavity Pressure and Warpage of Polyoxymethylene Thin Walled Injection Molded Parts: Experiments and Simulations

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Abstract. Process analysis and simulations on molding experiments of 3D thin shell parts have been conducted. Moldings were carried out with polyoxymethylene (POM). The moldings were performed with cavity pressure sensors in order to compare experimental process results with simulations. The warpage was characterized by measuring distances using a tactile coordinate measuring machine (CMM). Molding simulations have been executed taking into account actual processing conditions. Various aspects have been considered in the simulation: machine barrel geometry, injection speed profiles, cavity injection pressure, melt and mold temperatures, material rheological and pvT characterization. Factors investigated for comparisons were: injection pressure profile, short shots length, flow pattern, and warpage. A reliable molding experimental database was obtained, accurate simulations were conducted and a number of conclusions concerning improvements to simulation accuracy are presented regarding: pvT data, mesh, short shots, cavity pressure for process control validation as well as molding machine geometry modelling. Eventually, a methodology for improved molding simulations of cavity injection pressure, filling pattern and warpage was established.

Keywords: Thin-wall injection molding, process simulation, warpage, optimization.
PACS: 44.05.+e, 47.11.Df, 89.20.Bb

INTRODUCTION

The mechanical components which are part of a hearing aid are typically made of thermoplastics and are used to encase the electronics and the rest of the mechanical parts. These components are also referred to as the shell parts. They are characterized by having a relative complex geometry, being thin walled, having long flow lengths, having low tolerances, consisting of small details, and having large requirements to the surface finish. To aid with reducing the cost and time in connection with the development of new hearing aids simulation software can be used. Currently available software can simulate the molding and cooling processes, and hereafter warpage. However, there have been difficulties with predicting the correct values of warpage on the shell parts. It is therefore the objective of this work to analyze and simulate the warpage of thin walled shell parts with the Moldex3D eDesign software and potentially improve the predicted values of warpage. A simplified shell part cavity, resembling a hearing aid shell, has been manufactured including pressure and temperature sensors in the injection molding tool. A semi-crystalline polymer, namely polyoxymethylene (POM), was employed. The produced simple shell parts have been compared with simulations conducted with the same process parameters, to validate the software. The warpage has been measured with a tactile coordinate measuring machine (CMM) on the injection molded parts.

The physical behavior behind warpage of polymer injection molded parts is determined by the stiffness of the component and the level of differential shrinkage. There can be several reasons for differential shrinkage: different wall thicknesses throughout the part, non-uniform mold temperatures, orientation effects (e.g. orientation of polymer chains is different along and across the flow direction), and dissimilar volumetric shrinkage (e.g. due to variation in packing pressure) [1]. To further elaborate on the simulation part of injection molding it is generally accepted that all input data are important, i.e. uncertainties in material data, process settings, and boundary conditions will generate simulation results not reflecting the actual problem [2]. The focus in this work has been to reflect the importance of using: the complete geometry of the molding system (including mold, cooling channels, and even machine barrel), an accurate mesh, using material data for the actual used material as well as pressure-dependent viscosity (which has an effect in the packing phase).

As far as the material data are concerned, it can prove to be difficult to obtain data representing the material characteristics for defined injection molding conditions. Particularly, pvT data for semi-crystalline materials have been shown by Zuidema et al. and Gao et al. [3, 4] to be dependent on the cooling rate at which they have been characterized. They showed that at very low cooling rate (0.017°C/s) it matched data from the available database, but at higher cooling rate (40°C/s), the crystallization transition is shifted to lower temperature. Carrubba et al. [5] have also showed that pvT models are only fitting at low cooling rates. Several studies [6, 7] conclude that packing pressure is one of the clearly dominant factors which influence the cavity condition and product quality. Packing pressure is dominant, and in addition, if the effect of pressure on the melt viscosity is considered, the deviation between the predicted and the experimental pressure evolution is substantially reduced [8, 9]. The general trend from current literature on validation of warpage prediction shows limitations [10-12]. This is due to the fact that simplified two-dimensional geometries have been commonly investigated instead of more complex three-dimensional geometries. Deviations of predicted warpage encountered in previous works have been in the order of 0.2-0.4 mm, whereas this work aims at reaching deviations of 0.02 mm.

EXPERIMENTS

Part geometry

A tool with a thin-wall shell part cavity has been manufactured, with three integrated pressure sensors. Many of the hearing aid shells resemble the design seen in figure 1. The test part is designed similar to a typical hearing aid shell, but without all the internal micro features in order to simplify the molding process and its numerical calculation. The overall geometry of the part can be seen in figure 1(b), also with the inclusion of the pressure sensor locations, denoted P1, P2, and P3. The typical wall thickness of the part is 0.8 mm.

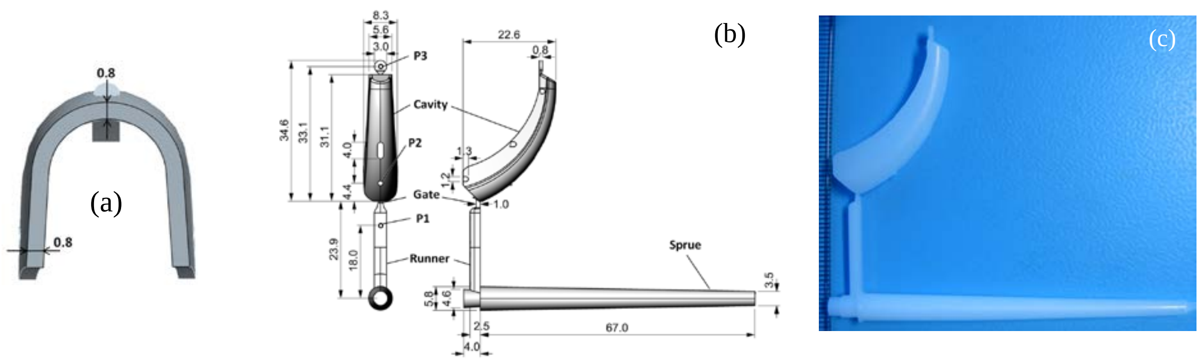


FIGURE 1. (a) Cross section of the part geometry. (b) Geometrical dimensions and sensor locations (P1, P2, and P3). (c) The injection molded hearing aid shell part. Material: polyoxymethylene Ticona Hostaform C 13021.

Validation and quality factors

To compare simulations and experiments, validation and quality factors were defined. The validation factors considered were the short shot pattern which gives a visual representation of the flow and the pressure which gives direct comparison between experiments and simulations. The quality factors are defined as three lateral measurements L1, L2, L3 and a height measurement H (see figure 2). The validation factors were used to first validate the simulation implementation and the quality factors were used to compare measured and simulated warpage.

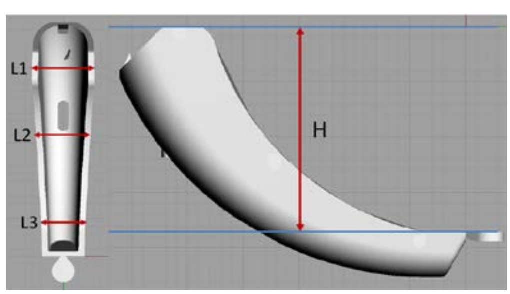


FIGURE 2. Lateral (L1, L2, L3) and height (H) measurements to quantify the warpage of the part.

The molding machine used for the experiments was an Arburg All Arounder 270A 350-70 Alldrive with an 18 mm plasticizing screw. The process parameters used were: injection speed = 25 mm/s, melt temperature = 220°C, mold temperature = 90°C, packing pressure = 75 MPa, packing time = 2 s, and cooling time = 6 s. The pressure curves obtained from the three pressure sensors are shown in figure 3. A pressure curve with a smooth transition to the packing phase was used, to avoid instability in the switchover pressure (see figure 3).

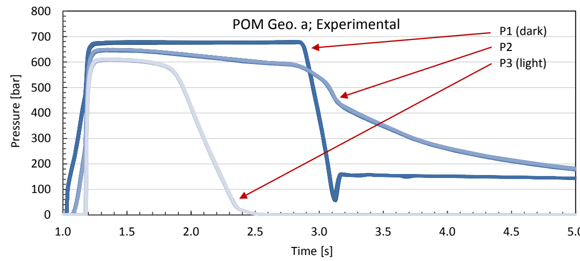
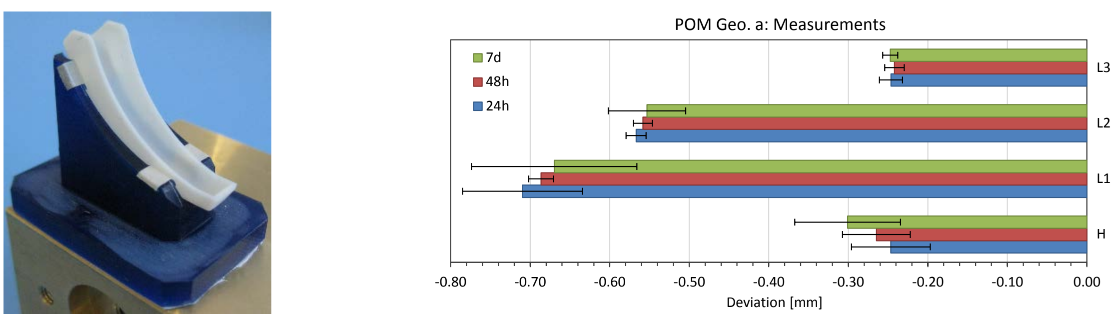


FIGURE 3. Experimental pressures from the pressure sensors in the mold. Sensors positions: P1 = before the gate, P2 = in the part, P3 = in an overflow at the end of the part. Average experimental standard deviation of pressure curves = 1.2 bar.

Warpage measurements

The warpage was measured using a coordinate measuring machine with a contact probe. The part was mounted on the 3D printed fixture seen in figure 4(a). This was done to avoid part deflection during the measuring procedure, as the fixture was made with a conformal shape. Also, the part is resting in the fixture with no actual clamping force applied.

The distances L1, L2, L3 and the height H (see figure 2) were measured. Measurements are presented as the measured value subtracted by the value from the CAD file of the mold, i.e. negative values indicate that the part is bending inwards. The uncertainty from the measuring procedure was found to be in the range of ±3 µm. Measurements were made after 24 hours, 48 hours, and 7 days to check whether the part warped any further due to residual stresses or viscoelastic effects. This was not the case as indicated in figure 4(b), due to average values lying within standard deviations. Measurement repeatability (i.e. standard deviation) of 2-10 µm was in general achieved for a single part. The standard deviation was higher (from 10 µm up to 100 µm) when including the repeatability of the molding process, i.e. measuring 10 different parts from the same production batch.



(a) (b)

FIGURE 4. (a) Part mounted in the fixture ready for warpage measurements. (b) Average of measurement results on 10 different parts at 24h, 48h, and 7 days after production. Errors bars indicate experimental standard deviation.

SIMULATIONS

To increase the accuracy of the simulations with respect to the experiments in terms of the pressure curves the following was considered: actual injection speed profile from the machine, actual packing pressure profile from machine, melt and mold temperature from machine and sensors respectively as well as material data for POM obtained from the manufacturer. Taking the mentioned aspects into consideration together with geometrical boundaries such as the cavity, mold, cooling channels, and machine barrel (see figure 5) improve the agreement between simulation and experiments [13]. The use of the actual machine geometry allows including the pressure drop through the geometry and the compressibility of the melt through the whole injection system as in the actual injection molding process.

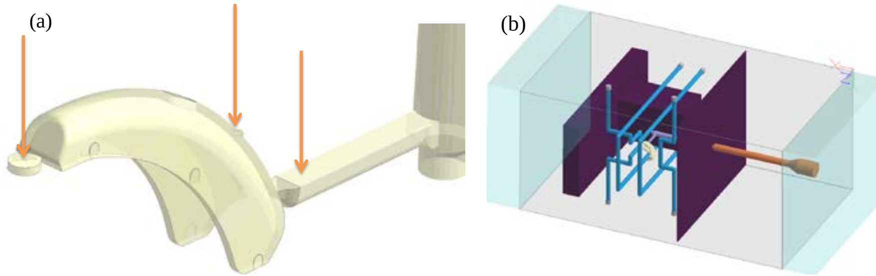


FIGURE 5. (a) Geometry imported into the simulation software, with sensor locations marked with arrows. (b) Simulation system including cavity, mold block, cooling channels and machine barrel. Total number of elements in the model: 3.5 million.

In order to further increase the simulation accuracy, different parameters were investigated. These include sensitivity of heat transfer coefficient (HTC) between part and mold, melt temperature, flow rate in cooling channels, mesh level, viscoelasticity, and pressure-dependent viscosity. The simulations showed very limited sensitivity of the injection pressure with respect to all parameters except from pressure-dependent viscosity and the HTC. The viscosity model used in Moldex3D eDesign R10 is the Cross-WLF which has the option to include the D3 coefficient, which is typically set to 0, and is controlling how much the viscosity depends on the pressure. The coefficient has been estimated using the procedure presented in [14], using the relation between the compressibility of the melt and its thermal expansion (from pvT data) and temperature-dependence on viscosity. Pressure-dependent viscosity is expected to have an effect during filling, but particularly on the packing pressure. The simulated pressure curves show high agreement with experiments after applying the pressure dependency on the viscosity. A short shot comparison can be seen in figure 6, which also shows good agreement between experiments and prediction of the flow. Figure 7 shows the pressure curves for all sensors and machine pressure for both the simulation and experiment.

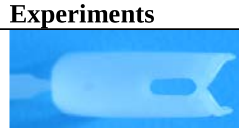
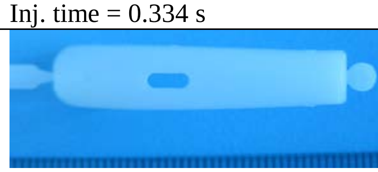
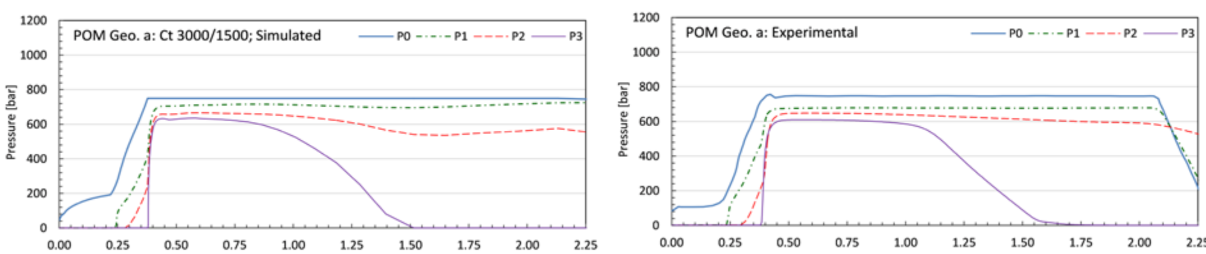
Experiments	**Simulation**	**Experiments**	**Simulation**
 Inj. time = 0.237 s		 Inj. time = 0.334 s	
 Inj. time = 0.312 s		 Inj. time = 0.379 s = 5 mm	

FIGURE 6. Flow front pattern validation: intermediate steps of the filling simulation at four different filling times.



(a) (b)

FIGURE 7. (a) Simulation results (including HTC and pressure dependent viscosity). (b) Experiments. P0 denotes the machine injection pressure.

The simulated warpage was measured following the same procedure as in the experimental measurement. The comparison is shown in figure 8 for the simulation with the pressure dependent viscosity and an optimized heat transfer coefficient of 3000 W/(m^2K) during filling and 1500 W/(m^2K) during packing. The agreement resulted to be satisfactory for L1, L2 and L3. However there is still some mismatch between the experimental and simulated height H which should be further investigated.

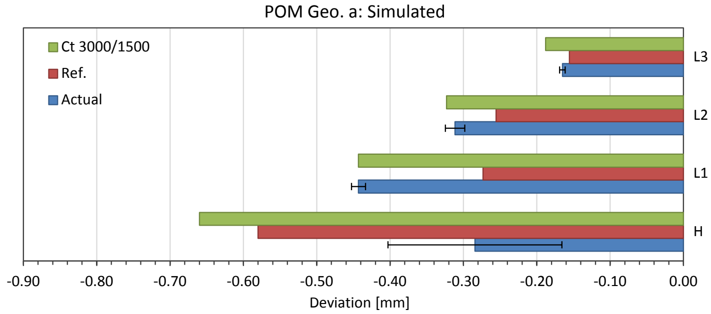


FIGURE 8. Comparison of experimental and simulated warpage results. '*Actual*' refers to the experimental measured warpage. '*Ref.*' refers to the warpage result in the reference simulation and the '*Ct 3000/1500*' refers to the simulated warpage including both pressure dependent viscosity and optimized values of HTC.

CONCLUSION

Experimental injection molding and simulation of three-dimensional thin walled shell parts were performed in this work. Experimental results created a reference for the comparison with the simulation of the process induced warpage. The injection molding process was simulated in satisfactory agreement with respect to the experiments. Optimized simulation results were mainly obtained after utilizing pressure dependent viscosity, including the machine barrel geometry, and optimized HTC values. The established simulation provided improved warpage calculations results as compared to the reference simulation.

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